



## Cost Optimization Through Value Engineering and Risk Analysis in Industrial Building Retrofitting Projects

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### Abstract

Retrofitting projects in industrial facilities are often prone to delays and cost overruns due to various technical, logistical, and operational risks. These challenges include limited working access, delayed material delivery, and regulatory constraints, all of which can significantly affect project efficiency and cost performance. This study aims to optimize project costs by integrating value engineering and risk analysis methods in retrofitting construction. A mixed-method approach was employed, combining case studies with statistical analysis using Structural Equation Modeling Partial Least Squares (SEM-PLS). Data were collected through surveys, expert interviews, field observations, and project documentation. The findings indicate that the integration of value engineering and risk analysis effectively reduces project costs without compromising quality. The application of value engineering resulted in an alternative solution using fire-rated drywall, which led to a cost saving of approximately IDR 5.36 billion or 9.63 percent of the original estimated cost. Additionally, the Life Cycle Cost (LCC) analysis showed that this alternative provided a more economical long-term solution, with a life cycle cost difference of 13.73 percent compared to the baseline material. These results highlight the practical benefits of integrating VE and risk management, offering a structured and data-driven framework for achieving cost-effective and sustainable outcomes in complex industrial retrofitting projects.

## Introduction

Value Engineering (VE) has long been recognized as a systematic approach to optimizing project costs without compromising quality and functionality. However, recent studies indicate that an overly narrow focus on cost reduction in VE may increase project risks, especially if not accompanied by comprehensive risk analysis. Vahedi et al. (2024) emphasized that although VE can generate significant savings, such reductions often introduce new risks, thereby making integration with risk analysis highly necessary and beneficial. This integrated approach not only avoids duplication of work but also enhances project economic value (value for money) through more thorough risk identification and appropriate mitigation strategies.

Retrofitting projects, particularly on old buildings or aging industrial facilities, face unique challenges during the construction process. Factors such as tight work schedules, suboptimal existing structural conditions, and limited historical construction data may increase both

technical and financial risks. A study by Hwang et al. (2017) found that retrofitting projects often face delays and cost overruns due to inherent risks. These risks may include uncertainties related to cost, completion time, and potential operational disruptions during retrofitting. These are often caused by constraints inherent in retrofit projects, such as limited budgets, restricted working hours, confined workspaces, difficulty transporting materials and equipment, disruptions to surrounding environments, limited technology and equipment, as well as challenges in regulations and policies (Qin et al., 2016).

Long-term project aspects are also a critical consideration in the integration of VE and risk analysis. Salem et al. (2020) compared several building retrofit scenarios in the UK and found that all VE options had lower Life Cycle Costs (LCC) than the baseline scenario. Risk analysis, as highlighted by Masengesho et al. (2020), plays a key role in estimating long-term costs and anticipating early-stage risks, which may help reduce total life cycle costs and enhance investment reliability.

Based on these findings, this study aims to explore optimal strategies for integrating value engineering and risk analysis, particularly in technically complex and highly uncertain retrofitting projects. The purpose of this research is to identify the factors that influence the effectiveness of integrating value engineering and risk analysis in minimizing the costs of retrofitting projects in industrial facilities; to develop a cost optimization method for construction investment based on VE that enhances efficiency and effectiveness; and to determine the feasibility of project investment costs using a Life Cycle Cost Analysis (LCCA) approach supported by risk analysis during the VE development phase. Through a combined framework of VE and risk management, the study is expected to offer a reliable and sustainable approach to improve construction cost performance while mitigating potential risks.

## Literature Review

### Value Engineering

Value Engineering (VE) is a systematic method aimed at increasing the value of a project by optimizing its functions while minimizing costs. Originally introduced in the 1940s by Lawrence D. Miles at General Electric, VE was designed to reduce production costs without compromising quality. It later expanded into the construction sector to address cost overruns and delays, particularly in large infrastructure projects (Chen et al., 2022). VE follows structured stages, including information gathering, function analysis, creativity, evaluation, development, and recommendation. The cost model developed by Fahrni & Spätig (1990) aids in identifying project components with the highest cost impact, guiding VE application. Studies show that VE can lead to significant cost savings, such as a 10% reduction in road construction projects (Amir & Zakia, 2018), and also improves quality and time efficiency through better collaboration and planning (Petersen et al., 2005; Ramanathan, 2014; Hameri & Heikkilä, 2002).

Furthermore, VE is increasingly integrated with advanced tools like Building Information Modeling (BIM), enhancing decision-making and cost control through real-time and detailed data analysis (Zanni et al., 2019). Life Cycle Cost Analysis (LCCA) also complements VE by evaluating long-term cost-effectiveness of construction alternatives, particularly in energy-efficient buildings (Zinzi & Mattoni, 2019). Beyond cost efficiency, VE supports sustainability and ecological harmony in construction (Nwaogbe et al., 2025; Kibert et al., 2000; Park et al., 2010). However, project complexity significantly moderates VE's effectiveness. Studies show that in more complex projects, VE's impact on cost and time efficiency may diminish, depending on how complexity is managed (Abdelrahman & Nassar,

2024; Natalia et al., 2022; Natalie et al., 2020). This highlights the need to consider project complexity as a moderating variable in VE implementation models.

## **Risk Analysis**

Project Risk Management is a critical process aimed at identifying, analyzing, and controlling risks that could impact project objectives. According to the Project Management Institute 2017 risk management consists of five stages: risk planning, identification, analysis, response, and monitoring. Each stage ensures a structured approach to manage uncertainties and maximize opportunities. Construction risks, as defined by Akintoye & Macleod (1997), are variables that cause uncertainty in cost, duration, and quality. These risks are especially prevalent in construction due to its complex, multi-organizational, and project-based nature (Hwang et al., 2017). Chapman & Ward (1998) emphasize that the early stages of a project carry the highest risks due to the strategic nature of decisions made at that phase.

Risk analysis involves both qualitative and quantitative methods to assess the likelihood and impact of identified risks (Tiusanen, 2017). Common tools include checklists, SWOT analysis, historical data review, and stakeholder discussions (Kajanus et al., 2012). The risk response phase includes strategies such as avoidance, reduction, transfer, and acceptance (Hendrastuti et al., 2024), while monitoring ensures ongoing control and the identification of new or secondary risks. A risk register summarizes key risk data such as descriptions, probabilities, impacts, and rankings (Siraj & Fayek, 2019). This structured approach helps maintain project stability and resilience across changing conditions.

## **Methods**

This research methodology was a mixed-method research design, as much as a procedural decision as a deliberate epistemological approach to capture the dynamic interaction between technical analysis and human judgment in construction project decision-making. The embedding of a qualitative and a quantitative study was felt to be essential to ease the tension between what can be statistically measured and what can only be experienced within the social and operational fabric of an ongoing industrial retrofitting project. Rather than addressing numbers and narratives as distinct fields, the research considered them as complementary dimensions and, in this way, the quantitative component could serve as validation for results identified through a qualitative approach based on lived practice.

Fieldwork was carried out at Michelin factory in Cikarang, a large industrial facility under a massive retrofitting process, which was both technically and managerially complex. This site was chosen not only because of its scale and relevance, but for its characteristic constraints: limited work space, high operation continuity, and complex coordination requirements between contractors and plant management. The period of the study was from January to April 2025 when the key construction processes were in progress for the project. This timing allowed for immersion in the real world of construction, thereby allowing for observation of the interactions of planning assumptions with unpredictable on-site realities - something that purely quantitative designs often do not capture.

Data collection followed a triangulated methodology, so as to ensure both analytical rigour and contextual relevance. The first source of understanding was based on direct field observations in which the researcher made a systematic effort to observe the cadence of daily construction activities, spatial limitations, and safety measures that guided technical decision-making. These observations were later augmented by in-depth interviews of key project stakeholders such as project managers, structural engineers, contractors and consultants who shared a unique perspective about risk, cost and performance prioritisation. To further

complement these qualitative findings, structured questionnaires were used for essential stakeholders and these allowed for wider perceptual trends to be captured and for the quantification of relationships to be established between critical factors influencing cost optimisation. The combining of narrative depth with quantitative accuracy contributed to a holistic understanding of the cost-risk nexus that exists in industrial retrofitting practices.

The quantitative analysis used Structural Equation Modelling - Partial Least Squares (SEM - PLS) using SmartPLS 4.0. This analytical strategy was applied not only because it is statistically robust, but also because it matches closely the conceptual complexity of the study. SEM-PLS allowed the researcher to test the existence of causal relationships between latent constructs such as material technical characteristics, risk management practices, and construction technology while at the same time the researcher could also include project complexity as a moderating variable. The resulting model captures the multidimensional nature of construction systems, in which the decision-making processes about materials, anticipation of risks and technological interventions rarely work in isolation from one another. In combining case level observations with SEM-PLS diagnostics, the study was able to keep a constructive dialogue between empirical phenomena and theoretical generalisations, thus achieving a research equilibrium that is often lacking in purely quantitative research designs.

The materials considered in this inquiry came from both primary and secondary sources in order to achieve a balanced convergence of empirical evidence and documentation from sources. Primary data were obtained through accompanied interaction with professionals and firsthand exposure to project activities-radicalising the findings from lived experience over conjecture. Secondary data, including project documentation, technical drawings, cost estimates and material specifications, were used to corroborate, situate and numerate the qualitative insights. This reciprocal methodological framework ensured that observations and statistical measurements informed and reinforced each other to produce a robust and intervalidated body of knowledge.

The method of applying Value Engineering (VE) was in a systematic, yet flexible order that tracked the working rhythm of a construction decision-making process rather than a fixed procedure handbook. The process started with the information phase in which cost structures together with the project functions were carefully mapped to extract the components that have the highest cost impact. This was followed by function analysis, with emphasis on the vital reason for each material or system used to allow the team to question whether current selection had in fact provided optimum value. The creative phase allowed alternative ways of thinking, based on both expert judgment and empirical feasibility, whereas the evaluation and development phase used Life Cycle Cost Analysis (LCCA) to consider the long term implications of each alternative. LCCA in this sense did not only work as a financial tool, but also as an ethical compass that ensured that immediate savings were not made at the cost of sustainability and future maintenance burdens.

Complementing the VE framework, a comprehensive risk analysis was conducted to identify potential vulnerabilities that were embedded in each of the design alternatives. This stage evolved beyond traditional risk identification to a more integrated approach to the risk/cost, time and operational continuity interaction. Both a qualitative assessment and quantitative assessment were used to estimate the likelihood and of the severity of potential disruptions, ranging from material degradation and installation challenges to the potential for regulatory compliance. These assessments informed the final decision-making process because it guaranteed that cost reductions were accompanied by credible mitigation strategies.

## Results and Discussion

The findings in this study are derived from an integrated analysis of both primary and secondary data sources. Primary data from project managers, contractors, and consultants revealed specific operational constraints such as limited workspace during retrofitting which directly influenced the feasibility of alternative materials. These insights were quantitatively corroborated by survey results showing 78% stakeholder agreement on the benefits of materials requiring less installation space. Secondary data, such as budget reports and technical drawings, quantified the cost implications and validated the technical feasibility of these alternatives. The integration of these datasets ensured that material choices were both operationally practical and economically justified.

### SEM-PLS Analysis Result

The Research Criteria and Sub-Criteria presented in Table 1.

Table 1. Research Variable and Main Factor

Variable	Main Factor	References
Technical Material Aspect (A)	Material Quality (A1) Work Method (A2) Material Durability (A3) Material Availability (A4) Environmental Impact (A5) Material Performance (A6)	(Urugal, 2023) (Monika Natalia et al., 2022) (S. Atabay, 2021)
Risk Analysis (B)	Risk Identification (B1) Risk Severity Level (B2) Risk Mitigation (B3) Risk Evaluation(B4)	(Othman et al., 2021)
Construction Technology (C)	Application of Construction Technology (C1) Use of Project Management Software (C2)	(Khan et al., 2025)
Cost (D)	Material Cost (D1) Labor Cost (D2) Equipment Cost (D3) Cost Savings (D4) Risk Cost (D5)	(Chen et al., 2022) (Li et al., 2021) (Enshassi et al., 2019)
Time (E)	Scheduling (E1) Project Completion Time (E2) Project Delay (E3) Risk Response Time (E4)	(Aksu & Atabay, 2024)
Project Complexity (F)	Project Scale (F1) Type of Material (F2) Construction Method (F3)	(Lin et al., 2023)

Table 1 presents the research variables and their main factors used in this study. The dependent variables are Cost [D] and Time [E], which assess the project's economic and temporal performance. Cost [D] is analyzed through five sub-factors, including Material Cost [D1], Labor Cost [D2], Equipment Cost [D3], Cost Savings [D4], and Risk Cost [D5]. Similarly, Time [E] is examined via Scheduling [E1], Project Completion Time [E2], Project Delay [E3], and Risk Response Time [E4].

The independent variables consist of three main components. First, Technical Material Aspect [A], which emphasizes construction material considerations such as Material Quality [A1], Work Method [A2], Durability [A3], Availability [A4], Environmental Impact [A5], and Performance [A6]. Second, Risk Analysis [B], which focuses on comprehensive risk management through Risk Identification [B1], Severity Level [B2], Mitigation [B3], and Evaluation [B4]. Third, Construction Technology [C], which assesses technological integration using factors such as the Application of Construction Technology [C1] and the Use of Project Management Software [C2].

A moderating variable, Project Complexity [F], is introduced to evaluate how complexity factors influence the relationship between the independent and dependent variables. This variable is characterized by Project Scale [F1], Type of Material [F2], and Construction Method [F3]. The analysis is conducted using a structural equation modeling approach to examine the causal relationships between the independent variables (A, B, and C) and the dependent variables (D and E), with Project Complexity [F] acting as a moderator that potentially strengthens or weakens these relationships.

Table 2 Reflective Measurement Model Evaluation

Criteria	A	B	C	F	D	E	Description
Loading Factor (> 0.7)	>0.7	>0.7	>0.7	>0.7	>0.7	>0.7	Strong correlation of each indicator
Composite Reliability / Cronbach's Alpha (> 0.7)	0.90	0.80	0.81	0.86	0.93	0.91	The instrument has good reliability
Average Variance Extracted (AVE)	0.62	0.63	0.83	0.78	0.79	0.74	Latent variables explain more than 50% of variance in each indicator
Discriminant Validity (AVE > latent correlation)	✓	✓	✓	✓	✓	✓	Each variable is distinct and measures different constructs
Cross Loading (Fornell-Larcker Criterion)	0.79	0.79	0.91	0.88	0.89	0.86	Each variable's AVE is greater than correlations with other variables

The evaluation of the Reflective Measurement Model for all latent variables Technical Material Aspect (A), Risk Analysis (B), Construction Technology (C), Cost (D), Time (E), and Project Complexity (F) demonstrates that the measurement instruments used in this study meet the necessary reliability and validity standards: (1) Loading Factors for all indicators under each latent variable exceed the threshold value of 0.7. This indicates a strong correlation between indicators and their respective constructs, confirming indicator relevance; (2) Composite Reliability and Cronbach's Alpha values for all variables range from 0.80 to 0.93, surpassing the minimum requirement of 0.7. This implies that each construct has high internal consistency and reliability in measuring the intended latent variables; (3) The Average Variance Extracted (AVE) values for all variables are above 0.5, with the lowest at 0.62 and the highest at 0.83. This confirms that each latent variable can explain more than 50% of the variance in its indicators, supporting convergent validity; (4) Discriminant Validity is fulfilled for all constructs, as indicated by AVE values that are greater than their correlations with other latent variables. This shows that each variable is distinct and measures a unique construct, thus avoiding overlapping constructs; (5) Fornell-Larcker Criterion test confirms discriminant validity through cross-loading values, where the AVE for each variable is higher than its correlation with other constructs. Cross-loading values range from 0.79 to 0.91, reinforcing the distinctiveness of each latent construct in the model.

Table 3.  $f^2$  (Effect Size) the Ranked Influence Toward Cost (D)

Rank	Predictor	$f^2$ Biaya
1	Construction Technology	0.541
2	Risk Analysis	0.379
3	Value Engineering	0.275

Table 4.  $f^2$  (Effect Size) the Ranked Influence Toward Time (E)

Rank	Predictor	$f^2$ Waktu
1	Construction Technology	0.424
2	Value Engineering	0.379
3	Risk Analysis	0.374

R<sup>2</sup> Values:

Cost (D): 0.797 (strong)

Time (E): 0.746 (strong)

Project Complexity (F): 0.488 (moderate)

Q<sup>2</sup> Predictive Relevance:

Cost (D) : 0.619 (strong predictive power)

Time (E) : 0.525 (moderate-strong)

Project Complexity (F) : 0.349 (acceptable)

Table 5. p-Values for Direct Effect

Relationship	Path Coefficient	T-Statistic	p-value
Risk Analysis (B) → Cost (D)	0.339	2.989	0.003
Risk Analysis (B) → Time (E)	0.377	2.912	0.004
Construction Technology (C) → Cost (D)	0.389	3.759	0.000
Construction Technology (C) → Time (E)	0.385	3.282	0.001
Technical Material Aspect (A) → Cost (D)	0.289	2.633	0.008
Technical Material Aspect (A) → Time (E)	0.379	2.767	0.006

Table 6. p-Values for Indirect Effects (Mediated by Project Complexity - F)

Indirect Path	Coefficient	T-Statistic	p-value
Risk Analysis (B) → F → Cost (D)	0.221	3.135	0.002
Construction Technology (C) → F → Cost (D)	0.193	2.955	0.003
Technical Material Aspect (A) → F → Cost (D)	0.222	2.747	0.006
Risk Analysis (B) → F → Time (E)	0.175	2.428	0.015
Construction Technology (C) → F → Time (E)	0.152	2.511	0.012
Technical Material Aspect (A) → F → Time (E)	0.176	2.273	0.023

The analysis reveals that all direct and indirect relationships in the structural model are statistically significant at the 5% level, confirming the robustness of the proposed framework. Technical Material Aspect (A), Risk Analysis (B), and Construction Technology (C) significantly influence both Cost (D) and Time (E), either directly or indirectly through the mediating role of Project Complexity (F). Among these, Construction Technology (C) exhibits the strongest overall impact, supported by high path coefficients and low p-values. Project Complexity (F) functions as a key mediator that channels the effects of A, B, and C onto project outcomes, emphasizing its strategic importance in construction project management. These results underline the critical roles of technical design decisions, risk

considerations, and technological implementation in optimizing project performance, making them essential factors in retrofitting and industrial project planning.

### Value Engineering (VE) Method

The Fire Protection Project is located at Jalan Raya Lemah Abang No. 3 Km 58, Karangsari, East Cikarang District, Bekasi Regency, West Java 17530. The project is owned by PT. ABC and carried out by PT. XYZ with a 12-month implementation duration. The investment value for this project is Rp55,657,450,160.

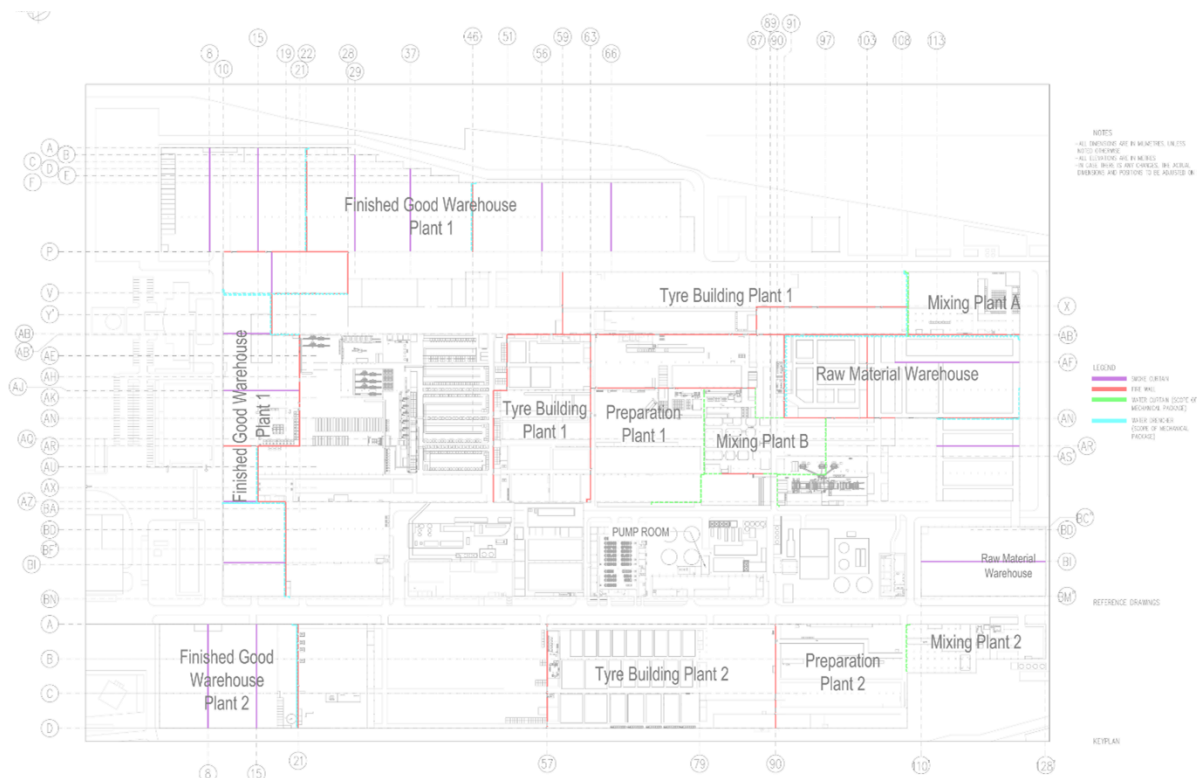


Figure 1 Site Plan

The Fire Protection Project by PT XYZ in Cikarang aims to construct a fire separation system (Fire Separation Package) in several key facilities, including: (1) Finished Goods Warehouse; (2) Preparation Plant 1 & 2; (3) Raw Material Warehouse; (4) Mixing Plant (A, B, and Plant-2). The primary objective of this project is to enhance the safety and resilience of the facility against fire risks through the construction of structures and systems that comply with fire safety standards. The scope of work includes structural construction (such as foundation work, steel structures, and concrete), architectural works (such as the installation of AAC block walls and fire-resistant panels), as well as utility installations (including fire-rated doors and smoke curtain systems).

### Information Phase

The information phase plays a crucial role in ensuring a comprehensive understanding of the product, process, or service before proceeding to the next stage of the Value Engineering process. Adequate information allows for better-informed decisions, enabling the design of solutions that enhance the value or efficiency of the subject being analyzed. To conduct a cost model analysis, a cost overview of the Fire Separation system was developed. The initial calculation employed a Pareto Analysis to identify the most significant cost items in construction work that could be further evaluated using Value Engineering. This approach is

based on the Pareto Principle, which suggests that 80% of total costs typically come from 20% of components. A cost breakdown model was then created by sorting work items from the highest to lowest cost and computing their cumulative percentages. The resulting budget plan is presented in the accompanying table 7.

Table 7. Budget Plan

Description	Amount	%
	IDR	
<b>Structural Works</b>		
Site Construction Work	343.603.076	0,60%
Concrete Work	793.630.500	1,38%
Metal Work	26.580.614.224	46,19%
<b>Architectural Works</b>		
Site Construction Work	2.060.690.000	3,58%
Masonry Work	106.920.000	0,19%
Metal Work	260.000.000	0,45%
Thermal And Moisture Protection Work	22.508.601.360	42,70%
Doors And Windows Work	1.525.076.000	2,65%
Finishes Work	953.190.000	1,66%
Special Construction Work	257.400.000	0,45%
<b>Subtotal</b>	<b>55.657.450.160</b>	

Based on the Pareto distribution principle, work items that account for more than 20% of the total cost are generally considered potential candidates for Value Engineering. The objective is to enhance the value or function of these items, thereby reducing overall project costs or increasing functionality and value across the entire project. The Pareto diagram illustrating the Fire Protection work can be seen in Figure 2.

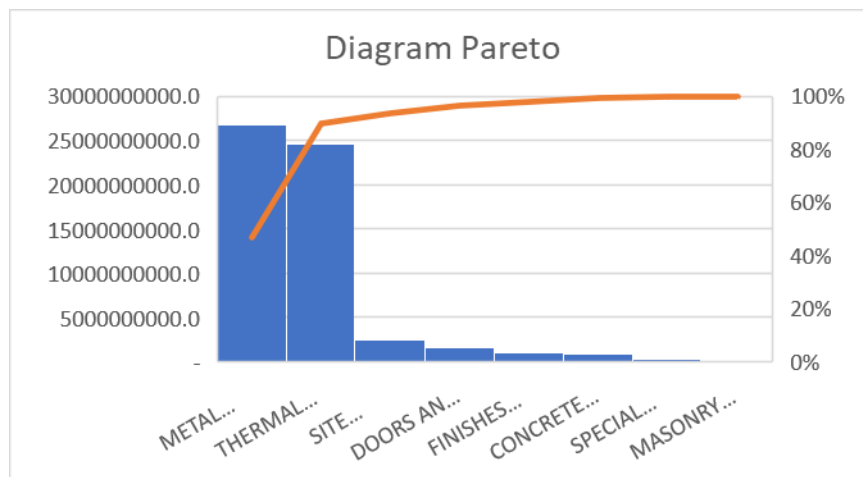


Figure 2. Pareto Diagram

Secondary data comprising budget reports, technical drawings, and material specifications enabled a precise cost breakdown and technical performance assessment. Budget documents identified that Thermal and Moisture Protection accounted for 42.70% of the total cost (IDR 22.51 billion), which was validated against technical drawings showing the required subframe structure for sandwich panels.

## Function Analysis Phase

The next stage is function analysis. This analysis aims to define the function of each work item to be evaluated, so that appropriate cost-saving strategies can later be determined for those items. One method that can be used in function analysis is the FAST (Function Analysis System Technique) Diagram. By using the FAST Diagram, Value Engineering becomes more than just a cost-cutting method; it also reviews the basic functions that serve as a reference for selecting alternative designs.

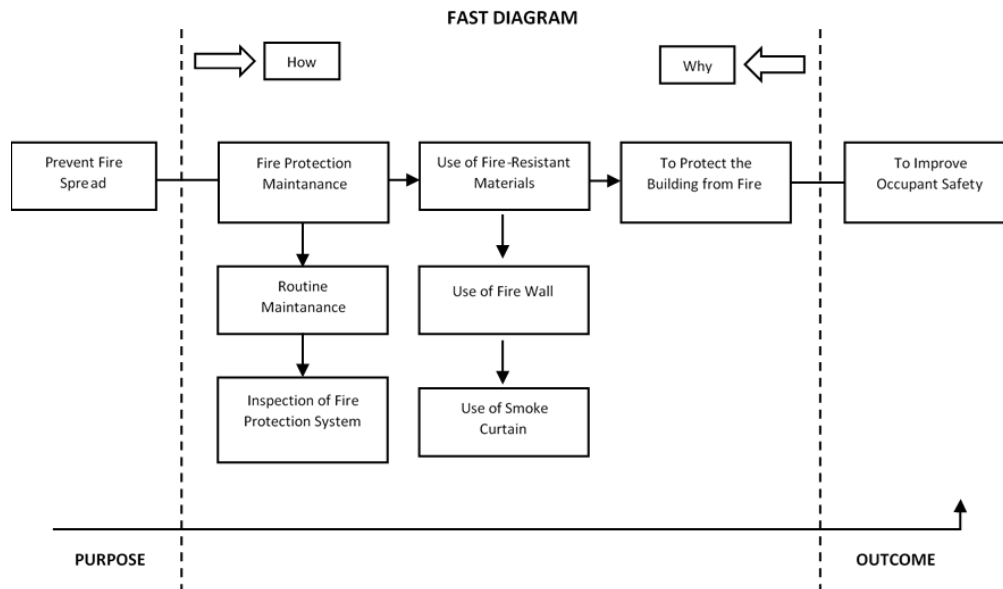


Figure 3. FAST Diagram

FAST (Function Analysis System Technique) diagram illustrates the functional relationship within the fire separation system, focusing on the primary objective of preventing fire spread. This is achieved through two main approaches: maintaining the fire protection system such as routine maintenance and inspections and using fire-resistant materials, including fire walls and smoke curtains. These actions serve the broader purpose of protecting the building from fire and ultimately enhancing the safety of its occupants. The diagram emphasizes that Value Engineering is not merely about cost reduction, but also about ensuring that essential functions are preserved or improved through thoughtful design alternatives.

## Creative Phase

The creative phase aims to identify possible ways to generate ideas related to the needs and expectations in the application of value engineering. Based on the Pareto diagram produced during the information phase, the work item with the highest cost in the total project budget is the thermal and moisture protection work. There are alternatives available for the thermal and moisture protection work. Existing plan specifies the use of sandwich panels, while a potential alternative is fire-rated drywall. The installation of sandwich panels requires a steel subframe to support the wall system. However, fire-rated drywall does not require a steel subframe, as it is already equipped with its own lightweight steel structure. In terms of installation, sandwich panels can be installed more quickly compared to fire-rated drywall. However, the installation process requires a relatively large space for the erection of the steel subframe and the sandwich panels themselves. On the other hand, the installation of fire-rated drywall only requires space for worker access, such as scaffolding. In this project case, construction activities are carried out while the machinery is in operation, resulting in very limited space provided by the owner. From a cost perspective, fire-rated drywall materials are

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less expensive compared to sandwich panels. Additionally, since fire-rated drywall does not require a steel subframe, it further reduces the demand for steel materials.

Table 8. Alternative Comparison

	<b>Existing</b>	<b>Alternative</b>
Material	Sandwich panel Rockwool	Drywall fire-rated
Fire-rated	2 hours	2 hours
Lifespan	20 tahun	20 tahun
Steel Requirement	Requires steel subframe	Has its own structural frame
Install Duration	Faster	Slower
Space Requirement	Requires large space for subframe erection and sandwich panel installation	Doesn't require a large space, just for scaffolding only

### Evaluation Phase

The evaluation phase aims to assess the alternatives generated during the creative phase by examining the advantages, disadvantages, and implementation feasibility of each option. This evaluation is applied to two wall material alternatives: Rockwool sandwich panels (existing option) and fire-rated drywall (proposed alternative).

Table 9. Material Alternatives Evaluation

Description	Existing (Rockwool Sandwich Panel)	Existing (Rockwool Sandwich Panel)	Alternative (Fire-Rated Drywall) -	Alternative (Fire-Rated Drywall) -
	Advantages	Disadvantages	Advantages	Disadvantages
Initial Construction Cost	<ul style="list-style-type: none"> <li>- Stronger and more stable structure</li> <li>- Resistant to temperature changes</li> <li>- Longer lifespan</li> </ul>	<ul style="list-style-type: none"> <li>- Higher initial cost</li> <li>- Requires steel subframe for installation</li> </ul>	<ul style="list-style-type: none"> <li>- Lower installation cost</li> <li>- Easier installation due to no subframe needed</li> </ul>	<ul style="list-style-type: none"> <li>- Shorter lifespan compared to sandwich panels</li> <li>- More vulnerable to impact</li> </ul>
Fire Resistance	Material has high fire resistance	Requires additional protection in certain areas	Fire-rated with good fire resistance	Fire resistance is still lower than that of sandwich panels
Energy Efficiency	<ul style="list-style-type: none"> <li>- Better thermal insulation</li> <li>- Reduces cooling load</li> </ul>	Higher installation cost	Can be combined with additional insulation materials	Lower thermal insulation compared to sandwich panels
Maintenance Cost	<ul style="list-style-type: none"> <li>- Minimal maintenance</li> <li>- Resistant to</li> </ul>	Higher initial cost	Lower initial cost	More frequent maintenance due to vulnerability to

	moisture and corrosion			moisture and damage
Flexibility and Modification	Solid structure, but difficult to modify	Less flexible for design changes	Easier to modify or renovate	Less durable than sandwich panels in the long term
Construction Time	Faster installation if subframe is already available	Requires specialized labor	Faster installation as no additional subframe is needed	Longer finishing process due to repainting requirements

The analysis was conducted on key cost components, including materials, labor, equipment, and metal work requirements. The evaluation results indicate that the alternative use of fire-rated drywall offers a lower initial investment value, amounting to IDR 18,186,511,278, compared to the existing Rockwool sandwich panel system, which costs IDR 22,508,601,360. This results in a cost efficiency difference of IDR 4,322,090,082. Furthermore, in terms of metal work, the use of Rockwool sandwich panels requires additional subframe structures, which increases the cost to IDR 26,751,994,224. In contrast, fire-rated drywall does not require a subframe, resulting in a total cost of only IDR 25,712,345,850. The cost savings in this aspect amount to IDR 1,039,648,374.

Table 10. Alternative Material Cost Evaluation

	Existing	Alternatif
	Sandwich panel Rockwool (IDR)	Drywall fire-rated (IDR)
Material Cost	20.257.741.224	15.485.479.115
Labor Cost	1.350.516.082	1.620.619.298
Equipment Cost	900.344.054	1.080.412.865
Total	22.508.601.360	18.186.511.278
Saving Cost	<b>4.322.090.082</b>	
	Drywall installation costs are more efficient	
Metal Work	Need steel subframe for sandwich panel	No need steel subframe
Cost	26.751.994.224	25.712.345.850
Saving Cost	<b>1.039.648.374</b>	

Overall, in terms of installation cost and structural requirements, the fire-rated drywall alternative is more economical than the existing option. The calculated savings reach 9.63%, which exceeds the standard Value Engineering (VE) threshold of 7%. Consequently, a Life Cycle Cost (LCC) analysis will be conducted to evaluate the cost over the construction's service life. In the value engineering process, a systematic approach is required to evaluate and compare various alternative solutions based on a set of relevant criteria. One of the methods used to support objective and measurable decision-making is the Multi-Decision Criteria Analysis (MDCA). To identify the most optimal fire-resistant partition material for an industrial building retrofitting project, an evaluation was conducted on two material alternatives: Rockwool Sandwich Panels and Fire-Rated Drywall. This evaluation is based on the principles of Value Engineering and considers several technical and economic criteria relevant to the project's needs, such as cost efficiency, technical performance, and implementation flexibility on site.

Table 11. MDCA – Value Engineering Evaluation Phase

No	Criteria	Weight	Existing (Sandwich Panel Rockwool)		Alternative (Fire-Rated Drywall)	
1	Initial Construction Cost	25%	3	High cost	5	More affordable
2	Fire Resistance	20%	5	2 hours	5	2 hours
3	Material Lifespan	15%	5	Better Insulation	4	Good Insulation
4	Maintenance Cost	15%	4	Low maintenance	2	More frequent repairs
5	Flexibility & Modification	10%	2	Difficult to modify	4	Easy to modify
6	Construction Time	10%	3	Slower due to subframe	4	Faster without it
7	Space Requirement	5%	2	Requires large space	5	Limited space acceptable
	<b>Total</b>	<b>100%</b>	<b>3.7</b>		<b>4.2</b>	

Based on the evaluation of the two material alternatives Rockwool Sandwich Panel and Fire-Rated Drywall considering seven key criteria (Initial Construction Cost, Fire Resistance, Material Lifespan, Maintenance Cost, Flexibility and Modifiability, Construction Time, and Space Requirement) along with their respective weights, the total weighted score obtained was 3.7 for Rockwool Sandwich Panel and 4.2 for Fire-Rated Drywall. These results indicate that Fire-Rated Drywall is superior overall, particularly due to its lower initial cost, higher flexibility, shorter construction time, and more efficient space utilization, despite requiring more frequent maintenance and having a slightly shorter material lifespan. Therefore, Fire-Rated Drywall can be recommended as a more efficient, flexible, and economical material choice for this construction project.

## Development Phase

### Life Cycle Cost Analysis (LCCA)

Life Cycle Cost (LCC) analysis using the Net Present Value (NPV) method is employed to calculate the total investment cost of an asset over its service life by considering the time value of money. This calculation includes the initial cost (such as construction and procurement), replacement cost (for certain components), operational and maintenance costs, and the salvage value (the residual value of the asset at the end of its life cycle).

$$\text{Maintenance Cost} = A \times \frac{(1 - (1 + i)^{-n})}{i}$$

Notes :

A = Annual maintenance cost

i = interest rate

n = Total year

$$LCCA = \text{Initial Cost} + \text{Maintenance Cost} - \text{Salvage Value}$$

In project planning and development, owners are often faced with various alternative options regarding materials, products, or systems to be used. In addition to technical considerations, cost is also a critical factor that must be taken into account. Life Cycle Cost Analysis (LCCA)

calculates the total cost, including initial cost, replacement cost, operational and maintenance costs, salvage value, and other related expenses. The LCCA method estimates future-year costs in terms of their present value. In this study, LCCA is applied to a case study involving the implementation of a retrofitting project. The research focuses on the use of LCCA because this method considers a range of relevant factors, such as initial investment cost, expected operational and maintenance costs, future replacement or upgrade costs, as well as environmental or social factors that may influence the total cost. Thus, LCCA provides a valuable framework for evaluating the economic aspects essential for making long-term investment decisions within a specific project timeframe.

Table 12. Life Cycle Cost

	<b>Existing</b>	<b>Alternatif</b>
	Sandwich panel (IDR)	Drywall fire-rated (IDR)
Initial Cost	22.508.601.360	18.186.511.278
Operational Cost		
Annual Maintenance Cost	478.860.662	563.365.485
Interest rate 12%		
Time (n) = 20 tahun	3.576.822.721	4.208.026.730
Replacement Cost	No need for replacement for 20 years	No need for replacement for 20 years
Salvage value	2.009.696.550	1.623.795.650
Total	24.075.727.531	20.770.742.358
Difference	<b>3.304.985.173</b>	

Life Cycle Cost Analysis (LCCA) quantified the long-term financial advantage of the alternative. Using cost figures from budget reports and maintenance projections from expert interviews, LCCA revealed that over 20 years, fire-rated drywall had a 13.73% lower life cycle cost (IDR 20.77 billion) compared to sandwich panels (IDR 24.07 billion). This LCCA finding, when combined with cost reduction identified in the Evaluation phase became a pivotal driver in the material selection decision. The lower total ownership cost over 20 years, despite slightly higher annual maintenance, aligned with stakeholder priorities for long-term economic efficiency.

### Risk Analysis

Sandwich panels with Rockwool cores are widely used in modern construction due to their combination of structural strength, thermal/acoustic insulation, and high fire resistance. However, despite these advantages, this material also presents several potential risks, including corrosion of the metal layer, joint leakage, and physical damage from impact. This risk analysis comprehensively examines various technical, financial, and operational threats, including their impact on firewall performance and life cycle cost.

Table 13. Risk of Sandwich Panel

No.	Risk	Cause	Impact
1	Corrosion on metal surface	High humidity exposure, corrosive chemicals	Reduced structural integrity and fire resistance
2	Leakage at joints	Damaged fire-resistant sealant, improper sealing	Fire/smoke spreading through gaps
3	Physical damage from impact	Operational activities (e.g., forklifts)	Cracks/dents on panels, high replacement cost

Table 14. Risk Assessment of Sandwich Panel

Risk	Likelihood	Impact	Risk Level (L×I)	Classification
Corrosion on metal surface	3	4	12	High
Leakage at joints	2	4	8	Medium
Physical damage	4	3	12	High

Table 15. Risk Mitigation – Sandwich Panel

Risk	Mitigation
Corrosion on metal surface	- Use premium anti-corrosion coating (epoxy) - Install dehumidifiers in moist areas
Leakage at joints	- Inspect fire sealants every 6 months - Use certified fire-rated sealants
Physical damage	- Install protective barriers (guard rails) - Conduct SOP socialization
Standard non-conformance	- Involve certified SNI/NFPA inspectors during installation - Perform pre-installation material testing

Drywall, as a popular construction material, offers several advantages such as fast installation, lightweight properties, and fire resistance especially in its fire-rated variant. However, it also introduces various technical, operational, and financial risks that must be proactively managed. This risk analysis aims to identify potential failures such as cracking, moisture damage, or loss of fire-rating and their impact on safety, cost, and compliance.

Table 16. Risks of Fire-Rated Drywall

No.	Risk	Cause	Impact
1	Surface cracking	Vibration, material shrinkage, moisture	Reduced aesthetics and fire resistance
2	Moisture damage	Water exposure, poor ventilation	Warping/mold, replacement required
3	Fireproof layer peeling	Improper coating application, material aging	Loss of fire-resistant properties
4	Fire resistance test failure	Insufficient drywall thickness or firestop quality	Certification failure, increased fire hazard

Table 17. Risk Assessment – Drywall

Risk	Likelihood	Impact	Risk Level (L×I)	Classification
Surface cracking	4	3	12	High
Moisture damage	3	4	12	High
Fireproof layer peeling	3	4	12	High

Table 18. Risk Mitigation – Drywall

Risk	Mitigation
Surface cracking	- Use fire-resistant elastic compound for repair - Install expansion joints in vibration-prone areas
Moisture damage	- Use moisture-resistant drywall - Ensure adequate ventilation
Fireproof layer peeling	- Recoat every 3 years using intumescent paint - Provide application training for maintenance team

Fire resistance failure	- Verify drywall thickness (min. 15 mm with coating) - Test samples in accredited lab
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Table 19. Risk and Mitigation Cost Comparison (20 Years)

Parameter	Existing (Rockwool Sandwich Panel)	Alternative (Fire-Rated Drywall)
Dominant Risk	Corrosion, physical damage	Moisture, cracking
Severity Level	High (due to high replacement cost)	High (due to frequent failures)
Mitigation Cost (Improvement)	IDR 444,762,225	–
Maintenance Cost (Annual)	IDR 191,832,821	IDR 257,090,125
20-Year Maintenance Total	IDR 4,281,418,639	IDR 5,141,802,500

Table 20. Value Engineering Development Scoring

No	Criteria	Existing (Sandwich Panel)	Alternative (Drywall)
1	LCC Cost	3 – IDR 24.1 B	5 – IDR 20.8 B
2	Risk Level	3 – High	4 – High
3	Mitigation Cost	4 – IDR 4.28 B	3 – IDR 5.14 B
4	Salvage Value	5 – IDR 2.0 B	4 – IDR 1.6 B
	<b>Total Score</b>	<b>15</b>	<b>16</b>

Risk analysis, based on field observations and historical maintenance data, identified different dominant vulnerabilities: corrosion and joint leakage for sandwich panels, versus moisture damage and surface cracking for drywall. The integration of risk severity scores (primary data) with mitigation cost estimates (secondary data) showed that, despite drywall's higher mitigation costs, its lower replacement risk in confined-space installation made it the more viable option for this project's operational context. These risk insights were evaluated alongside LCCA and VE outputs, ensuring that the chosen alternative did not compromise fire safety or operational performance. Although drywall presented higher mitigation costs, its reduced installation space requirement and lower likelihood of replacement in confined areas outweighed these drawbacks when assessed through the integrated decision framework. Based on the comparison between Rockwool Sandwich Panel and Fire-Rated Drywall across four key criteria Life Cycle Cost (LCC), Risk Level, Mitigation Cost, and Salvage Value with their respective scoring weights, the total weighted score was 15 for the Sandwich Panel and 16 for the Drywall alternative. This indicates that Fire-Rated Drywall is the more favorable option overall, particularly due to its lower life cycle cost and slightly better risk level, despite having higher mitigation costs and a lower salvage value. Therefore, Fire-Rated Drywall can be recommended as a more efficient and viable material alternative for this project.

### Decision Phase

Based on the comparison between costs before and after the implementation of Value Engineering (VE), it can be observed that there is a total cost reduction of IDR 5,361,738,456, which is equivalent to 9.63% of the initial total cost. This reduction is primarily driven by optimizations in several construction work components, particularly in metal work and thermal and moisture protection work.

Table 21. Post-VE Cost Estimate

Description	Before VE	After VE
	IDR	IDR
<b>Structural Works</b>		
Site Construction Work	343.603.076	343.603.076
Concrete Work	793.630.500	793.630.500
Metal Work	26.580.614.224	25.712.345.850
<b>Architectural Works</b>		
Site Construction Work	2.060.690.000	2.060.690.000
Masonry Work	106.920.000	106.920.000
Metal Work	260.000.000	260.000.000
Thermal And Moisture Protection Work	22.508.601.360	18.186.511.278
Doors And Windows Work	1.525.076.000	1.525.076.000
Finishes Work	953.190.000	953.190.000
Special Construction Work	257.400.000	257.400.000
<b>Total</b>	<b>55.657.450.160</b>	<b>50.295.711.704</b>
<b>Cost Savings</b>	<b>5.361.738.456</b>	
	<b>9,63%</b>	

The decision-making stage in the Value Engineering process is carried out by comparing various alternatives based on predetermined technical, functional, and economic criteria. Based on the evaluation results, the fire-rated drywall alternative achieved the highest score in two comparative analyses: 16 (in terms of LCC cost, risk, mitigation, and salvage value) and 4.2 (in terms of initial cost, fire resistance, flexibility, construction time, and space efficiency), compared to the Sandwich Panel Rockwool. Furthermore, the total project cost analysis shows that the implementation of this alternative can generate savings of IDR 5,361,738,456, or approximately 9.63% of the initial budget. Considering its technical advantages and significant cost efficiency, fire-rated drywall is determined to be the most optimal solution and is recommended for implementation in the project.

The Value Engineering (VE) process synthesized these inputs to evaluate material alternatives. The creative phase, informed by both field observations (primary) and cost estimates (secondary), proposed replacing Rockwool sandwich panels with fire-rated drywall. Evaluation results demonstrated a 9.63% cost reduction (IDR 5.36 billion) driven by savings in metal work and thermal protection, corroborated by material specification data showing reduced steel usage.

This study has shown that Value Engineering (VE) and risk analysis are highly effective in improving the cost-effectiveness of the process and decision-making quality in the area of retrofitting in industries. This synthesis reinvents the notion of value, however, not as a simplistic cost-cutting tool, but as a multidimensional balance, with economic, performance, and sustainability requirements. Modern research supports such a shift, showing that the efficacious decisions in construction can be made when the notions of value and risk are viewed as interconnected variables as opposed to separate managerial areas (Vahedi, Khorvash, and Pakdel, 2024; Gunarathne et al., 2022). The empirically obtained results herein agree with this reasoning, as it can be seen that cost optimisation did not take place via material substitution, but rather via the mutual interaction of technical evaluation, risk foreseeing, and long-term investment logic.

The integration of the Life Cycle Cost Analysis (LCCA) will support the ever-growing awareness that the economic appraisal of long-term sustainability lies at the heart of sustainable creation of value. Previously, it has been proven by the literature that the sole focus on initial cost distorts the true value of any alternative (Salem et al., 2019; Zinzi and Mattoni, 2019). In line with these revelations, the present research finds that a fire-resistant drywall substitute albeit at the expense of higher maintenance costs gives better economic returns in the long run. This finding highlights the fact that the main ideal of VE lies in the maximisation of the value allocation throughout the life of the project, and thus financial and functional integrity are mutually accompanied.

Technology also takes a central stage in defining performance of the project. Empirical studies by Khan et al. (2025), Gouda Mohamed et al. (2024), and Tamara et al. (2021) confirm that the gap between design innovation and cost realism is closed by the application of Building Information Modeling (BIM) to VE processes. This evidence is echoed in the current study, which reveals that digital tools can increase the accuracy of the analysis and align its stakeholders, which results in a decrease in uncertainty and the increase in the predictability of the costs. Thus, technology is not a supportive tool, but a mechanism that promotes the joint and evidence-based decision-making that considers VE and risk frameworks.

The complexity of the construction decision-making process in terms of non-linear relationships among material performance, risk exposure and technology is represented in the methodological use of Structural Equation Modeling - Partial Least Squares (SEM multiplied with PLS) approach. SEM-PLS has been found to be effective in multidimensional models with latent variables (Hair et al., 2022; Abdelrahman and Nassar, 2024; Othman et al., 2021). The current study expands on this basis by showing that complexity of undertaking projects mediates the interaction between these factors and hence the assertion that the results of decisions are shaped by stratified interdependence as opposed to single-factor causal impacts.

The results of risk analysis help to understand the fragile nature of the relationship between operational vulnerability and mitigation cost. Enshassi et al. (2019) accentuated that the connection between prompt risk identification and cost is a prevention strategy, and Figueiredo and Kitson (2009) emphasised the role of the constant measurement in maintaining risk containment. These arguments are reflected in the current work since it was found that though drywall requires more maintenance, it has a more consistent risk profile in an environment of limitations. This makes it necessary to embed adaptive monitoring mechanisms, which will avoid the short-term benefits of long-term inefficiency.

The results also support a developing concept of sustainability as part of value optimisation. Chen and Wang (2022) and Masengesho et al. (2021) stated that sustainable construction does not only focus on financial aspects but also covers environmental and resource efficiency. The current study supports this view and it is shown that the chosen option of drywall improves the installation process and flexibility and remains economical. However, sustainability is not a permanent goal that requires constant re-evaluation with a changing operational and environmental environment.

The consequences are especially acute within the framework of retrofitting projects. According to Hwang et al. (2017) and Qin et al. (2016), retrofitting environments are associated with operational uncertainty and spatial constraints that require flexible materials and construction techniques. The continuity of operations with a minimum disruption follows the same principle in the current study where the fire-rated drywall was preferred in the pursuit of the continuity of operations. Lin et al. (2023) also highlighted that complexity is an active mediator in project systems and not a constraint. This perspective is supported by the present

results that show that the complexity of project design mediates the interplay between the technical and managerial decision-making and the consistent performance outcomes.

In addition to theoretical understanding, these results have an evident practical importance. Optimisation of costs needs to be integrated with governance that can bring together the value evaluation, risk management, and life-cycle thinking. Such integration has been demonstrated by scholars like Vahedi et al. (2024) and Khan et al. (2025) to be fully realized when provided with digital visualization tools that enable the team to simulate trade-offs prior to implementation. Thus, the industrial retrofitting management needs to change its views on the reactive problem-solving mode to the proactive design governance, i.e., the data, technology, and human expertise have to work in the continuous mode.

This research recognizes that it has a common limitation with the rest of the VE research. As Chen et al. (2022), Ramadhan and Kurniasari (2024), and others noted, most of the studies are still based on small-scale case evidence, and the technological integration is still subject to the organisational culture and maturity (Gouda Mohamed et al., 2024). Future studies would be able to build on the analysis of single-project and to longitudinal and cross-sectoral analyses and include how integrated VE-risk frameworks would change in different industrial settings. On the whole, the research would lead to a paradigm shift in construction management the shift towards the perception of efficiency as the systemic balance of cost, technology, risk, and sustainability, which would turn the process of cost optimisation into a value-driven and reflective process.

## Conclusion

This research addresses the stated objectives by developing a comprehensive model that integrates Value Engineering and Risk Analysis to optimize costs in industrial retrofitting projects. The SEM-PLS results confirm that technical material aspect, risk analysis, construction technology, and project complexity significantly influence project cost and time efficiency. Construction Technology (C) shows the strongest influence on Cost (D) and Time (E), with the highest path coefficients (e.g., 0.389 to D and 0.385 to E), and large effect sizes ( $f^2 = 0.541$  to D and 0.424 to E). Technical Material Aspect (A) and Risk Analysis (B) also have significant direct and indirect effects, with p-values  $< 0.05$  across all relationships. Project Complexity (F) plays a key mediating role, especially in transmitting the effects of A, B, and C to project outcomes. The model demonstrates strong explanatory power ( $R^2 = 0.797$  for D and 0.746 for E) and predictive relevance ( $Q^2 = 0.619$  for D and 0.525 for E), supporting its use in strategic planning and value-based decision-making for industrial retrofitting projects. The integration of Value Engineering and Risk Analysis was proven effective in reducing project costs by 9.63% and identifying risk-driven cost escalations. Furthermore, Life Cycle Cost Analysis (LCCA) revealed that fire-rated drywall is more economical than rockwool sandwich panels over the long term, with a 13.73% cost advantage though accompanied by higher associated risks. These findings contribute not only empirical evidence but also a practical decision-making framework that can be applied to complex retrofit projects. The research advances methodological integration by offering a validated model that enhances project efficiency through simultaneous cost optimization and risk management. Each of the three key outcomes short-term cost savings, long-term cost efficiency, and operational gains directly originated from specific analytical processes: VE quantified immediate savings in metal work and thermal protection, LCCA confirmed the superior life cycle value, and risk analysis verified operational feasibility without unacceptable safety trade-offs. This explicit linkage ensures the study's findings are both methodologically rigorous and practically actionable for future industrial retrofitting projects.

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## Compliance with Ethics Guidelines

The authors declare they have no conflict of interest or financial conflicts to disclose. This article contains no studies with human or animal subjects performed by authors.

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